HYDRODYNAMIC INVESTIGATION OF A SHALLOW TROPICAL LAKE ENVIRONMENT (LAGUNA LAKE, PHILIPPINES) AND ASSOCIATED IMPLICATIONS FOR EUTROPHIC VULNERABILITY

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Abstract

In this study, a three-dimensional (3D) hydrodynamic model was developed to investigate the water circulation characteristics of a shallow tropical lake environment (Laguna Lake, Philippines) under varying wind stress, watershed river discharge, and sea interaction (Manila Bay, Philippines) to elucidate hydrodynamic implications to eutrophic vulnerability. The analyses were based on field observations and numerical simulations covering long-term periods (dry and wet season) and intensive field measurements. The results demonstrated different circulation patterns and vertical current regimes in time and space that accentuated a thermally stratified lake environment in spite of a shallow water depth (2.5 meter average). In the wet season, current movement is generally toward Pasig River, the lake's only outlet, with embayment water mass moving in the clockwise direction. The dry season lake flow pattern was characterized by counter-clockwise gyre circulations, Pasig River backflow, and salinity intrusion. Wind forces showed strong influence on lake hydrodynamics due to the complex surrounding topography, steep land-lake thermal difference, regular passage of tropical storms and typhoons, and shifts in the monsoon wind direction. The resulting mixed layer hydrodynamics revealed important implications to the planktonic movement, nutrient recycling, and primary production of the lake. Long term continuous observations and numerical analyses also demonstrated the intrusion of seawater to Laguna Lake that potentially adds to its eutrophic vulnerability with the associated entry of nutrient and microorganism-rich polluted waters from Metro Manila.

Keywords: Delft3D, Hydrodynamics, Laguna de Bay, Modeling, Water quality

Introduction

The fresh waters of the world are collectively experiencing markedly accelerating rates of qualitative and quantitative degradation [1]. The scarce supplies of inland fresh-water are exploited by the rapidly expanding human population, growing industrial economy and extensive urbanization. These factors severely affect water quality and, hence, environmental integrity. The control and reversal of degradation requires proper economic and social valuation of fresh waters. The first step, ultimately, is a comprehensive understanding of the physical, chemical and metabolic mechanisms of these ecosystems. However, most current literature on general limnology remains temperate-based as tropical limnology only developed in the late 20^{th} century. Limnology in the tropics has only recently developed past the stage of exploration [2, 3]. In particular, only a small fraction of the research has focused on the mechanisms of shallow tropical lakes, despite the limnological significance of these aquatic ecosystems. The ecosystem response to environmental degradation considerably differs between tropical and temperate lakes [4]. The foundation of protective and diagnostic regulations of lakes is based on decades of scientific research on temperate lakes and cannot be readily applied to tropical lakes. Therefore, comprehensive research on tropical limnology is warranted for establishing a scientific foundation for the proper treatment and management of tropical inland ecosystems.

Laguna Lake, one of the largest lakes in Southeast Asia, is one of the most important natural water-resource bases in the Philippines. Strategically located at the center of an urban development, Metro Manila, it is the focal point of national and regional development efforts in the agriculture and fishery, water supply and energy sectors [5]. At the same time, however, Laguna Lake is stressed with competing water-users and continued environmental degradation from anthropogenic-based stressors. The dynamic interaction of the lake with Manila Bay through the Pasig River provides salt-water interaction, which makes it ideal for the fishery and aquaculture industries. However, nutrient-rich polluted water also discharges from Metro Manila and surrounding coastal provinces to the lake. As a result, massive fish kills have been a regular occurrence [5, 6] and has become a management priority. The pressures of both growing user-demand and declining water quality have increasingly stressed the value of scientific knowledge on understanding the mechanisms of the lake environment for the optimal and sustainable use of its water resources. A need for hydrodynamic and water quality research of Laguna Lake is warranted to generate reliable information for improving lake conservation and management programs.

This study investigates the hydrodynamic features of Laguna Lake with the use of intensive and extensive field surveys and high resolution numerical modeling analyses. The study primarily aims to clarify the circulation and transport features of a tropical lake ecosystem and provide information on water quality dynamics affecting critical ecosystem conditions. The implications for eutrophic vulnerability of the lake were elucidated based on the analyses of lake hydrodynamics. Climatic, hydrodynamic and bio-chemical parameters were measured using various data-logging sensors and water samplings. Long-term continuous measurements were established to capture seasonal and annual variations of environmental variables. A three-dimensional hydrodynamic model was set-up to evaluate the circulation and mass transport characteristics of the lake. The results presented in this paper could potentially provide insight into the physical-biochemical dynamics and functioning of shallow tropical lakes in urban environments in the Southeast Asian region and may correspondingly fill-in existing knowledge gaps in tropical limnology.

Materials and Methods

Laguna Lake Physical Environment

Laguna Lake (located at 14^{o}11’-14^{o}33’ N, 121^{o}03’-121^{o}29’ E) is the largest lake in the Philippines with a surface area of 900 km^2 (Figure 1). The lake is approximately maple leaf-shaped with four distinct lobes, namely, ‘West Bay’, ‘Central Bay’, ‘East Bay’, and ‘South Bay’, delineated by a total shoreline length of 285 km. The shallow average depth of 2.5 m accounts for its characteristic turbidity [5] with a Secchi disc transparency reading of less than 25 cm for low salinity intrusion years. The water level in the lake oscillates with an annual amplitude of approximately two meters. Laguna Lake has natural brackish waters due to its interaction with Manila Bay through the tidally affected Pasig River. The 27-km Pasig River serves as the only outlet of the lake. In the dry season, when the lake level is lower than Manila Bay, and when there is sufficient tidal fluctuation, the flow reverses. During the backflow of the Pasig River, the river discharges nutrient-rich water and the lake experiences an intrusion of polluted sea water, promoting fishery and aquaculture as the lake's most dominant economic function. The lake annually contributes approximately 85,000 metric tons of fish [7,8] to the fish supply of Metro Manila and nearby provinces. This accounts for approximately 40% of the total fish production through aquaculture in the Philippines. Fish pen belts and fish cage belts at specified locations in the lake, cover a total area of 100 km^2 and 50 km^2, respectively [4]. Silt-sized particles predominate in the surface sediments of Laguna Lake. However, clay-sized particles are abundant in West Bay likely due to the high yield of fine-grained sediments of the Pasig River and to the common occurrence of seawater intrusion-induced flocculation [9].

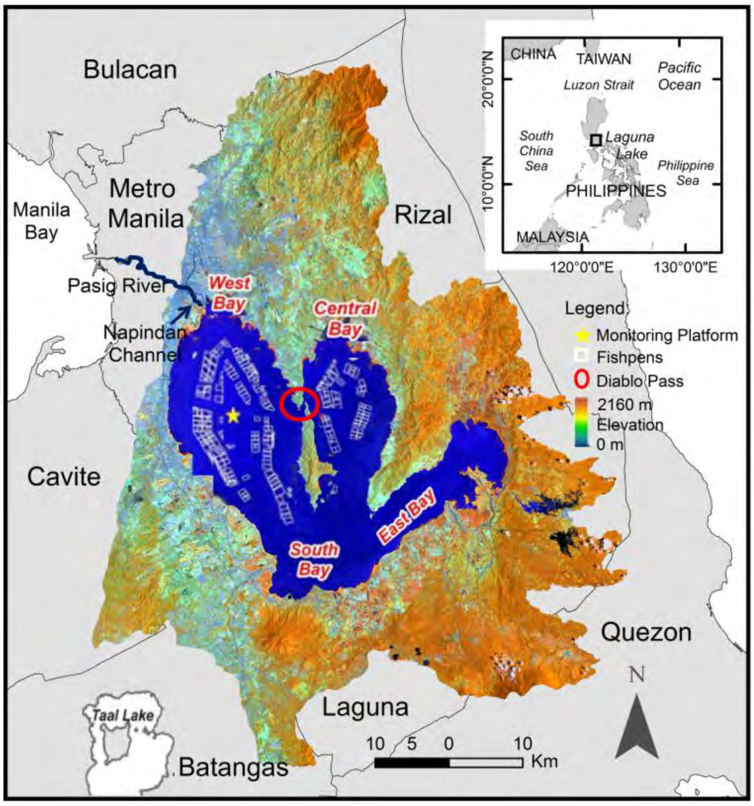

Figure 1. Location of Laguna Lake, Philippines. Shown also are the relative locations of Manila Bay, Pasig River, Napindan Channel, West Bay, Central Bay, East Bay, South Bay, and the Lake watershed

Field Surveys and Sampling Procedures

The continuous intensive monitoring of meteorological, hydrodynamic, and water quality parameters was facilitated through a monitoring platform constructed at the northwestern lobe of the lake (Figure 1). The platform was established as a part of the objectives for the collaborative data monitoring and research of the Laguna Lake environment between the Tokyo Institute of Technology, Japan (Nadaoka Laboratory), and the Department of Environment and Natural Resources, Philippines (Laguna Lake Development Authority).

The platform was configured to have both weather and water monitoring sensors. Parameters monitored were the salinity, density, conductivity, water temperature, dissolved oxygen, chlorophyll-a, turbidity, water depth, horizontal velocity, and wave height. The weather sensors (i.e., solar radiation, air temperature, humidity, atmospheric pressure, rainfall, and wind velocity) were connected to a separate data logger for data storage and retrieval. Several intensive and extensive joint field activities have been conducted since the formalization of the collaboration. The extensive lake field surveys conducted so far include: observations of the spatial distribution of chromophoric or colored dissolved organic matter (CDOM) and algal composition and their relationship with other water quality parameters; a groundwater discharge potential mapping using radon activity and resistivity distribution; watershed river discharge and water quality measurements; and extensive lake hydrodynamic and water quality surveys. The surveys were conducted during the dry and wet seasons to capture temporal variations in distribution.

Numerical Modeling

In order to reproduce the hydrodynamic conditions at the time of intensive measurements for analyses, the hydrodynamic component of Delft3D-FLOW (Deltares, The Netherlands) was utilized to simulate the physics of Laguna Lake. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic and transport simulation program that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcings [10]. Outputs from the model included three-dimensional distributions of the velocity, temperature, salinity, density, passive tracers, mixing coefficients and water level, among other hydrodynamic parameters. The required inputs include forcing due to wind, atmospheric pressure gradients, surface heat and water fluxes and open boundary conditions (e.g., tides). Due to the significance of wind waves in Laguna Lake, wave modeling was also incorporated. Delft3D-WAVE was used to simulate the evolution of wind-generated waves in the lake [11]. The Laguna Lake hydrodynamic model is a three-dimensional sigma coordinate, density-driven, hydrodynamic model laid-out on a horizontal and orthogonal curvilinear grid. A two year simulation (January 2007-January 2009) was carried out to capture field observation conditions. Observed weather conditions at the platform were utilized as inputs for the heat flux model component [12] and the meteorological forcing condition of the Laguna Lake model. The Pasig River was incorporated as a simple river model in order to include the interaction of Laguna Lake with Manila Bay. The open boundary of the model was located at the bay mouth of the Pasig River and was defined with a water level forcing boundary condition derived from the tidal components of Manila Bay. Watershed river discharges were incorporated into the model as positive discharge or flux points. The Sacramento model (Rainfall-runoff library, CRC for Catchment Hydrology Australia), was utilized to perform the hydrologic analysis of the rainfall-run-off transformation. It is a soil moisture accounting model that logically distributes applied moisture to various depths and energy states of the soil column based on soil moisture characteristics [13]. The model incorporates a two soil layer structure, the upper zone and the lower zone. Each layer consists of tension and free water storages that interact to generate soil moisture states and five runoff components. Partitioning of rainfall into surface runoff and infiltration into the lower zone storages depends on available storage of tension and free water in the upper zone. Movement of water from upper zone to lower zone is by process of percolation. Input data series are rainfall and evaporation, output is stream discharge. The input precipitation for each sub-basin was derived using rainfall data from stations within and around the sub-basin area, employing a normal weighting procedure. Evaporation on the other hand was estimated using daily pan evaporation information. Lake abstractions (e.g., irrigation, domestic water supply, power generation, etc.) were also integrated into the hydrodynamic model as negative discharges and fluxes. Bed roughness and eddy viscosity and diffusivity values were used as model calibration parameters. The model computational set-up is summarized in Table 1.

Table 1. Laguna Lake Hydrodynamic Model Computational Set-Up

Component	Condition
Computational mesh	Orthogonal curvilinear (80x113)x10 in sigma coordinate
Simulation period	730 days (January 2007-January 2009)
Initial condition	Observed temperature, water elevation, and salinity
Boundary condition	Astronomical tide, observed temperature/salinity
Meteorological forcing	Space varying wind[1], Murakami heat flux model [10,12]
Calibration parameters	Horizontal viscosity/diffusivity, bed roughness
Bottom roughness	Manning roughness[2]
Discharges	31 river discharges, 12 abstraction point
Additional parameters	Local weirs[3] for energy losses (aquaculture structures)

[1]Weather stations from Quezon City (Metro Manila), Los Banos (Laguna), Tayabas (Quezon) and Laguna Lake (monitoring platform) were utilized for generating space varying wind
[2]A Manning roughness coefficient of 0.015 was used for Laguna Lake and 0.040 for Pasig River
[3]Local weirs were used to represent fish pen structures in the model

Results and Discussion

Wind Temporal Dynamics

The Philippines has a tropical marine climate that is dominated by a wet season and a dry season and governed by prevailing wind conditions. The southwest monsoon brings heavy rains from May to October, while the northeast monsoon brings cooler and drier air from December to February. However, surface wind conditions typically vary inland depending on the landscape. Local topographic barriers cause deflections in the monsoon wind direction. Figure 2 shows prevailing wind conditions in the western lobe of Laguna Lake, 10 m above the water surface. Winds predominantly blow from the northwest during the southwest monsoon with magnitudes ranging between 3-8 m/s. The interaction of the northeast monsoon with the surrounding local topography results in a persistent southeasterly lake breeze from December to February. The topography of the watershed alters and provides variance in local weather conditions of the lake. Laguna Lake is bordered by the Sierra Madre mountain ranges in the northeast, the high Caliraya volcanic plateau in the east, and the mountain chains of the Laguna and Batangas provinces in the south and southeast.

Accordingly, the unequal heating of the land and water masses causes the movement of the overlying air and generates wind motions. A spectral analysis on the Laguna Lake wind was performed to evaluate the significance of these physics. The analysis revealed the periodicity and thermally induced nature of the lake breeze (Figure 3). The dominant wind period was 1 day (i.e., diurnal frequency). The diurnal signal correspondingly reflected the daily solar heating cycle. A strong coherence spectrum was observed between air temperature and wind, suggesting the lake wind is thermally induced [14] with a corresponding diurnal rhythm. This explains the observed diurnal wind pattern in Laguna Lake. Figure 2 shows the diurnal wind conditions in the lake each season. Winds are predominantly north-westerly with regular low values in the morning and peaks in the afternoon during the southwest monsoon season. Northeast monsoon conditions show winds blowing from the southeast with regular diurnal patterns of calm (m.v.2.4 m/s) mornings and intense (m.v.5.2 m/s) late afternoon breezes. Wind magnitudes peak much later in the afternoon and extend until early night time most likely due to the more stable solar irradiance of the season. This temporal wind dynamics will have important implications on the lake's mixing potential, correspondingly water quality distribution.

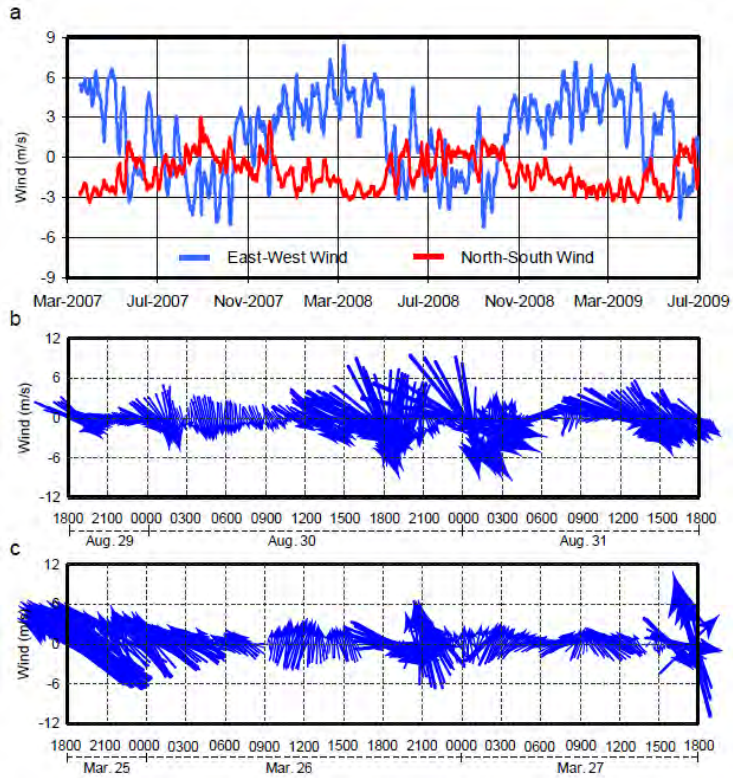

Figure 2. Temporal distribution of Laguna Lake wind conditions ((a) seasonal wind (b) wet season diurnal wind (c) dry season diurnal wind)

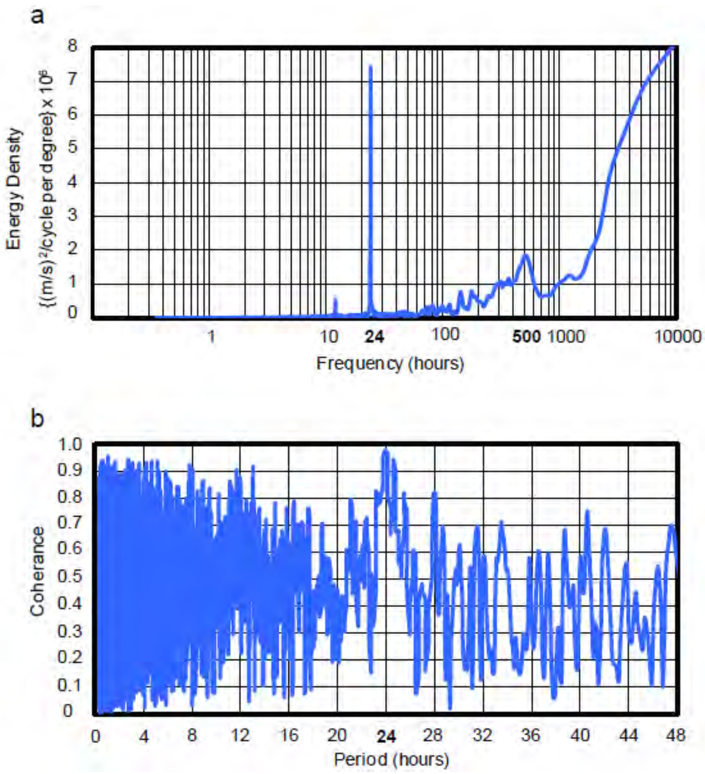

Figure 3. Power spectral density analysis of (a) wind spectrum (b) wind and air temperature coherance

Water Level Fluctuation and Seawater Intrusion

The Laguna Lake hydrodynamic model was calibrated and validated using hydrographic data from the platform and from monitored information collected by other agencies. Based on the comparison of observed and simulated data, the model was fairly accurate (Figure 4).

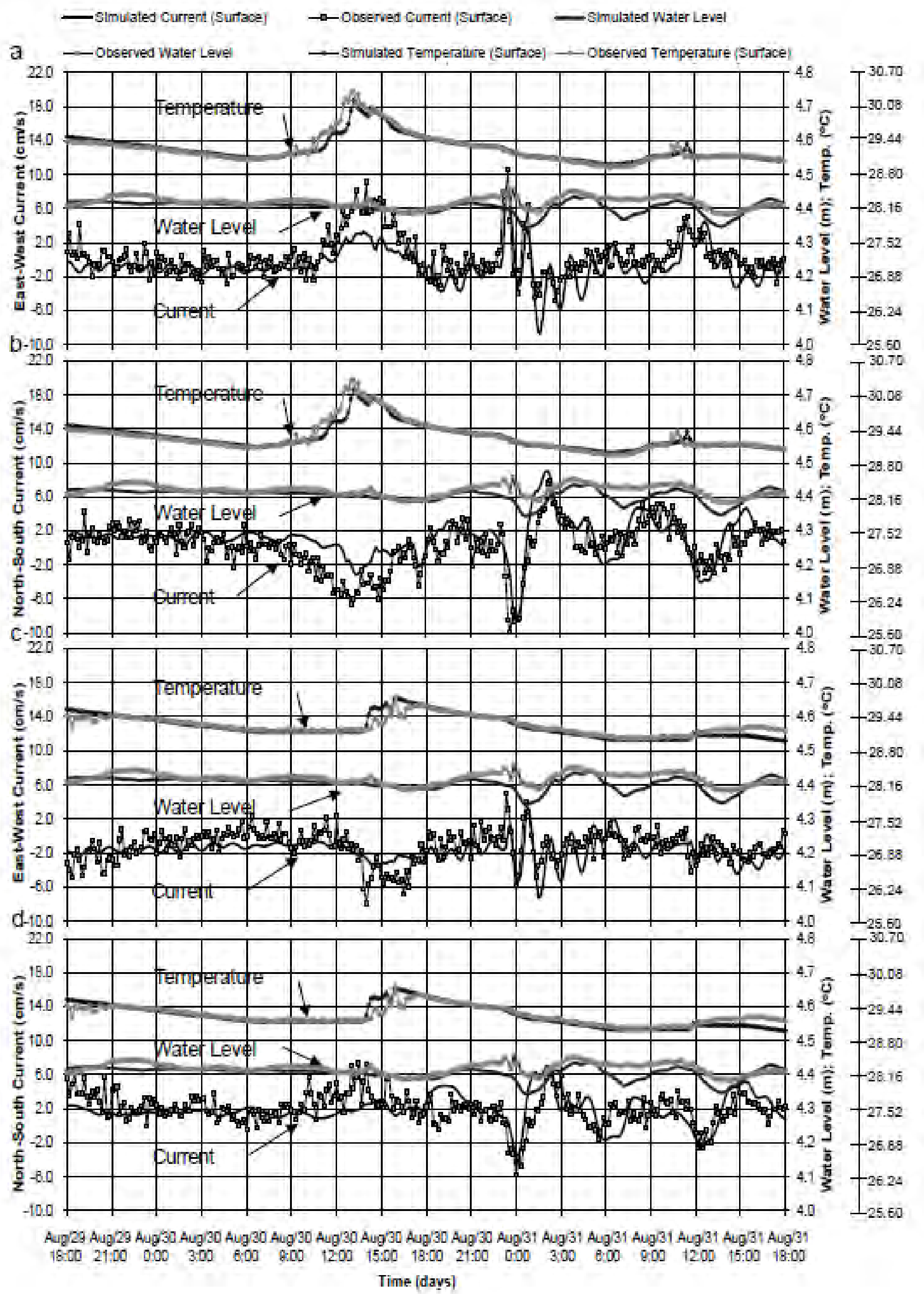

Figure 4. (A) Laguna Lake hydrodynamic wet season model performance for water level, temperature and velocity ((a) Near surface east-west directed flows (b) Near surface north-south directed flows (c) Near bottom east-west directed flows (d) Near bottom north-south directed flows)

The Laguna Lake water stage is principally the result of the dynamic balance between the watershed discharge, evaporation and tidal fluctuations at the downstream outlet (i.e., Manila Bay). With a continuously increasing trend, water abstraction for domestic, agricultural and industrial use is expected to have more significant effects on the lake water level. Figure 5 shows the annual water level and salinity intrusion time series of Laguna Lake and includes model validation. The tidal fluctuation at Manila Bay is also indicated.

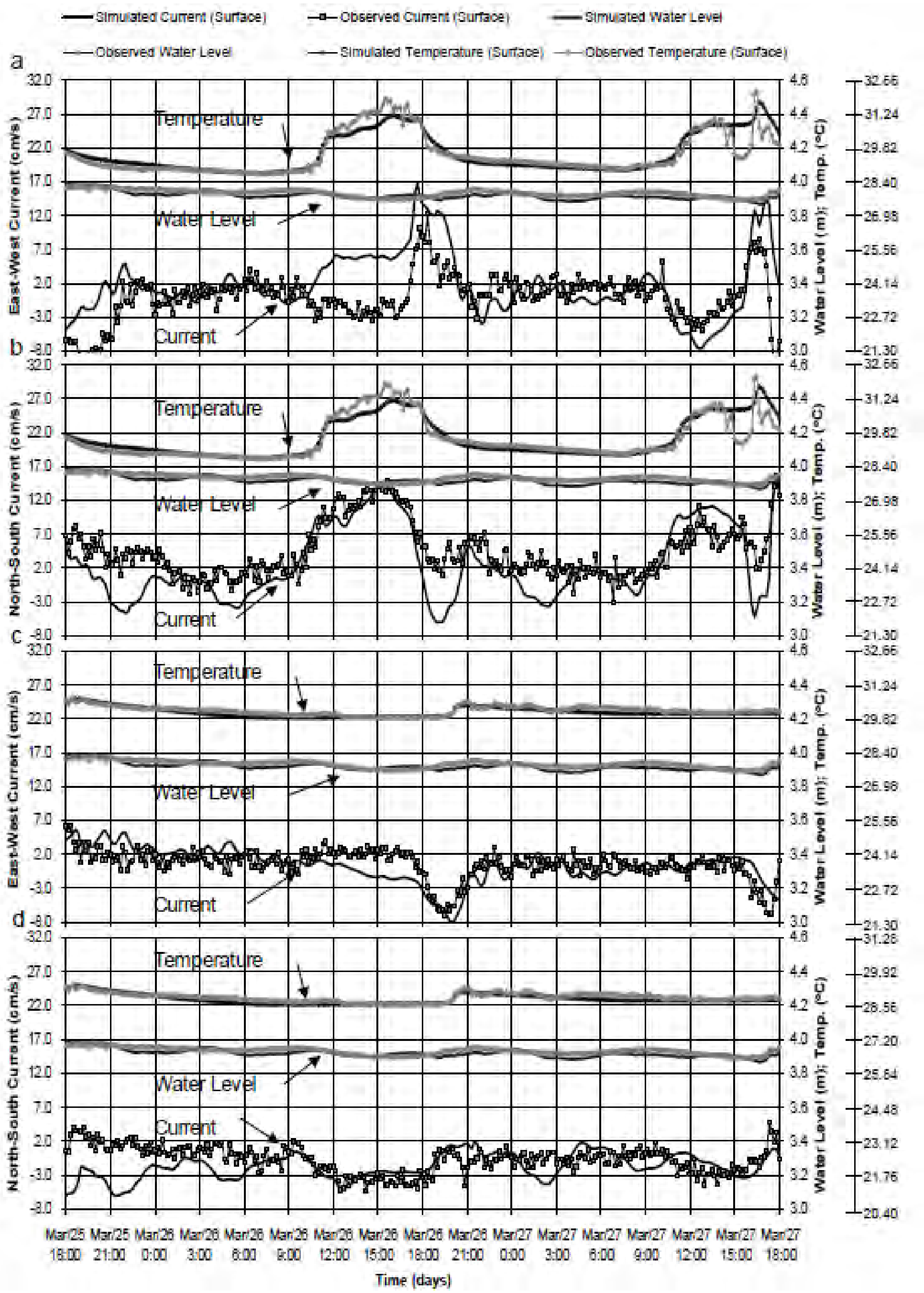

Figure 4. (B) Laguna Lake hydrodynamic dry season model performance for water level, temperature and velocity ((a) Near surface east-west directed flows (b) Near surface north-south directed flows (c) Near bottom east-west directed flows (d) Near bottom north-south directed flows)

The lake stage is observed to drop at the beginning of the dry season in December. It starts to fall below the Manila Bay tidal flooding level in January at a lake elevation of 0.60

meters a.m.s.l. The reversal of the bay-lake potential energy gradient correspondingly results to a lake-ward Pasig River flow which signals the lake intrusion. The water level continues to decline in succeeding months, strengthening the backflow, and hitting its peak in May at the lowest elevation of the lake. The lake stage begins to rise at the start of the rainy season in June. The water level difference between the bay and the lake decreases and the Pasig River backflow accordingly weakens. The condition remains in effect until the lake level exceeds the 0.60 meter a.m.s.l. elevation in July. Moisture sources continue to recharge the water volume of the lake in subsequent months; the lake volume reaches a peak in September. The highest recorded lake elevation was 4.1 meters a.m.s.l. Thereafter, the lake stage falls until the end of monsoon rains in October. The water level peaks again in late November to mid-December due to a late surge of passing typhoons. From this analysis, two inferences follow. First, the lake saltwater intrusion was seasonally modulated based on the potential energy gradient between Laguna Lake and Manila Bay. Its occurrence and intensity were dependent on the water balance of the lake. Second, the backflow occurs as a fluctuating signal and a function of the tide, rather than a single continuous event. Hence, the seawater intrusion was also tidally modulated. However, given the 27 km length of the Pasig River, the spring tide signal to saltwater flow was delayed.

Based on the numerical simulation, the lake salinity intrusion typically begins in January at a lake elevation of 0.60 meters a.m.s.l. as a weak, tide-fluctuating, saltwater inflow from the Napindan channel (which is connected to the Pasig River). Apparently, chloride levels were highest in the West Bay at concentrations >5 psu (Figure 6). The saline wedge nearly covered all of the west embayment and reached the central and eastern lobes through the Diablo Pas and the South Bay, respectively; however, these regions had relatively weak concentrations (<5 psu). Saline waters seldom penetrated the East Bay because of its remoteness and large volume of freshwater input from its immediate watershed. The intrusion event also signals the entry to the lake of polluted waters (solid and liquid waste) coming from Metro Manila and Manila Bay.

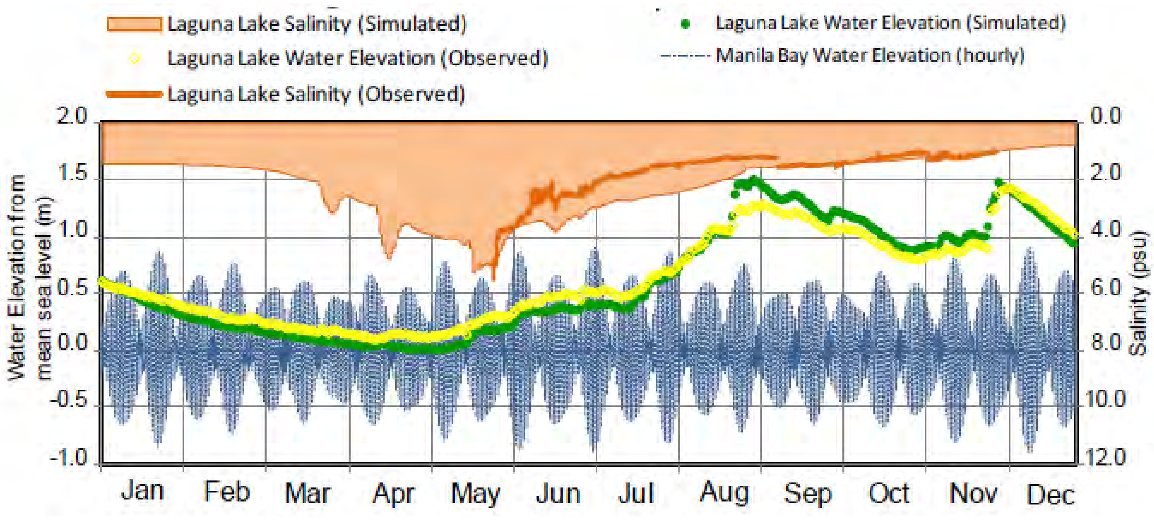

Figure 5. Laguna Lake model performance for water elevation and salinity (2008), together with Manila Bay water elevation

With the onset of the rainy season in June, the lake water level rose, and the bay-lake potential energy gradient eventually reversed signal. The Pasig River reverts to its normal flow direction. Accordingly, the intruded seawater was transported back to Manila Bay.

The complete flushing of the intruded saltwater was performed during the highest potential energy flow of the lake, which was in September. The duration of the seawater intrusion, from its entry until its eventual exit, spanned a total of 9 months from January to September. Figure 6 shows snapshots of the simulated salt water concentration distribution in Laguna Lake.

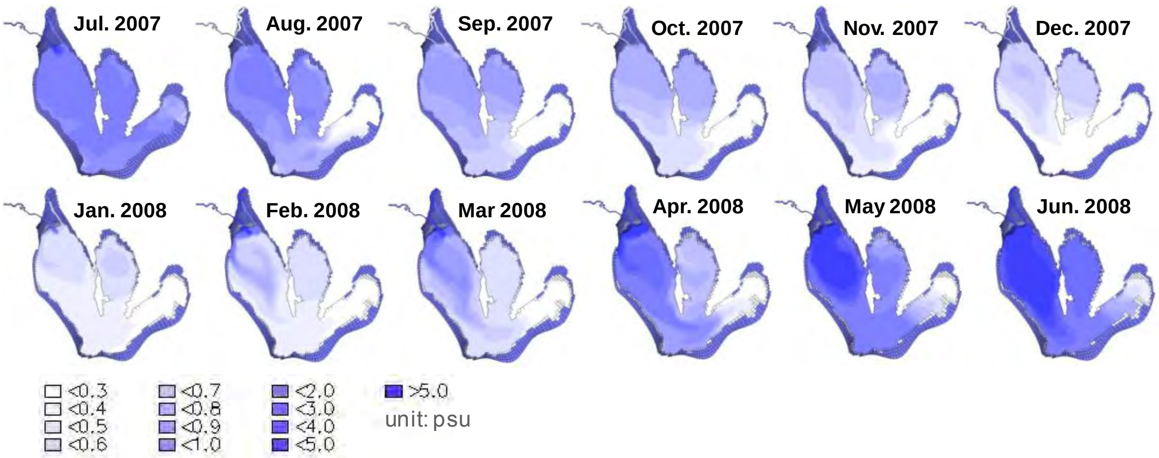

Figure 6. Snapshots of simulated Laguna Lake salinity concentration distribution in the near bottom

General Lake Circulation

The Laguna Lake circulation is defined primarily by three forcing factors: the watershed river discharge; the tidal fluctuation; and the wind stress. With a contribution of nearly 70% of the total lake inflow, discharges from sub-watersheds surrounding Laguna Lake significantly affected the general circulation of the lake. An accurate description of the potential energy gradient between Manila Bay and Laguna Lake is crucial for defining the flow of the Pasig River, which determines the general flow direction of the lake. Due to the shallow lake water depth, wind forcing provides considerable stresses that can generate significant surface wind-driven currents and bottom compensating flows. Therefore, the accurate quantitative description of the advective transport mechanism of the lake largely depends on the specification of these lake forcing factors.

Figures 7 and 8 show the simulated circulation patterns of Laguna Lake. The results demonstrate different circulation patterns and vertical current regimes for hydrodynamic conditions of the wet and dry seasons. During the wet season, the current movement is generally directed for outflow through the Napindan Channel because the embayment water mass moves in the general direction of the outlet. The general embayment circulation is anticyclonic. East Bay currents principally move toward the South Bay, while the weak clockwise gyre circulation of the Central Bay discharges to both the South Bay and the Diablo Pass. Currents converge in the West Bay and homogeneously flow northwest toward the Napindan Channel. The velocity magnitude is lowest (<5 cm/s) near the coasts and increases (to 5-10 cm/s) with respect to the depth toward the middle of the lake embayments. The reverse is true for the current distribution in the Central Bay. The fastest currents occur near the Napindan channel in the West Bay. The horizontal flow velocity distribution along the vertical is more or less uniform with minimal abrupt changes in the current pattern. The flow velocity demonstrated a minimum influence from the prevailing northwesterly wind of the season. The computed annual average lake outflow was 148.8 m^3/s. From the foregoing analysis, the positive potential energy gradient between Laguna

Lake and Manila Bay governed the dominant lake circulation pattern during the wet season and was primarily caused due to the high watershed discharge input.

Counter-clockwise gyre circulations dominate the lake current pattern in the dry season. All embayments demonstrated depth-averaged cyclonic water movement except for South Bay which exhibited a clockwise circulation. The results suggest a reversal of the lake-bay potential energy gradient that brought about a lake-ward Pasig River flow. Seawater intrusion occurred and lake outflow was restricted as a result. East Bay currents remained southward while the cyclonic water movement of the Central Bay only discharged through the South Bay as the Diablo Pass became an entry channel. Unlike the wet season, the velocity magnitude was highest (5-10 cm/s) near the coasts and decreased (<5 cm/s) with depth toward the middle of the lake embayments. Generally, the fastest currents were near the coasts and were not only concentrated adjacent to the Napindan channel in the West Bay. The depth-averaged current distribution indicated faster and more abrupt velocity fluctuations, particularly near the shoreline, in a gyre circulation pattern. The annual average backflow was computed at 12.6 m^3/s. The dry season flow pattern demonstrated a wind-driven, density-induced two layered current pattern along the vertical. A layering effect due to density differences was most likely enhanced by the intense solar heating and seawater intrusion of the season. Surface water movements showed a strong influence from the prevailing southeasterly wind with a compensating bottom current flow. The near-bottom flow was lake-ward as a result, with currents from the West, Central and South bays moving southeast. Hence, the counter-clockwise gyre circulation dominates the general water movement in Laguna Lake during the dry season. The current is primarily driven by the wind, and the density stratification defined the two-layered current pattern along the vertical. The seasonal variation in the lake's general circulation therefore provides an opportunity for seasonal dynamics in material transport and metabolic processing.

Hydrodynamics and Micro-Algal Distribution

Figure 9 shows the distribution of water quality parameters in the lake for both the wet and dry seasons. The lake demonstrated a low N:P ratio with high nutrient concentrations. The mean N:P ratios were 5:1 for the wet season and 3:1 for the dry season, much lower than the ideal Redfield ratio for phytoplankton growth. Nitrate algal-assimilation may be dominant, suggestive of a nitrogen-dependent environment common for tropical ecosystems. These types of ecosystems show the most sensitive biological response to nitrogen concentration fluctuations. Nutrient levels were nonetheless high with value ranges of 0.01-1.0 mg/l N and 0.04-0.2 mg/l P for the wet seasons and 0.01-1.7 mg/l N and 0.02-0.4 mg/l P for the dry seasons. Analysis of the N:P ratio for both seasons revealed interesting correlations with the algal biomass and phytoplankton class dominance. Areas with low N:P ratios showed high algal concentrations especially for the dry season, indicative of active nitrogen assimilation. The similarity in distribution between the N:P ratio and the algal concentration confirmed nitrogen as the limiting nutrient for algal growth in the lake. A quick view at the phytoplankton class distribution also reveals a strong association with the dominant lake algal group, diatoms. This phytoplankton group is the most adaptive to highly turbulent conditions and light gradients. They are also capable of synthesizing and sinking, for later redistribution in the water column under turbulent conditions. It is for these reasons that they are the most dominant algal group in Laguna Lake and represent a significant portion of the total algal biomass distribution. A study by Cuvin-Aralar et al. [6] on the effects of low N:P ratios in the phytoplankton community of Laguna Lake indicated the dominance of diatoms among all algal groups with the lowest N:P ratios. Thus, areas with low N:P ratios are conducive environments for diatom growth. This would explain the strong correlation between the N:P ratio and the phytoplankton biomass distribution observed in the lake. The high phytoplankton concentrations found in the East Bay for both seasons despite a relatively low nutrient supply can similarly be justified. Diatoms dominate the area because of the low N:P ratio. In addition, the east embayment of the lake has the longest fetch length, which translates to a stronger wind-induced mixing, as manifested by the observed turbidity distribution.

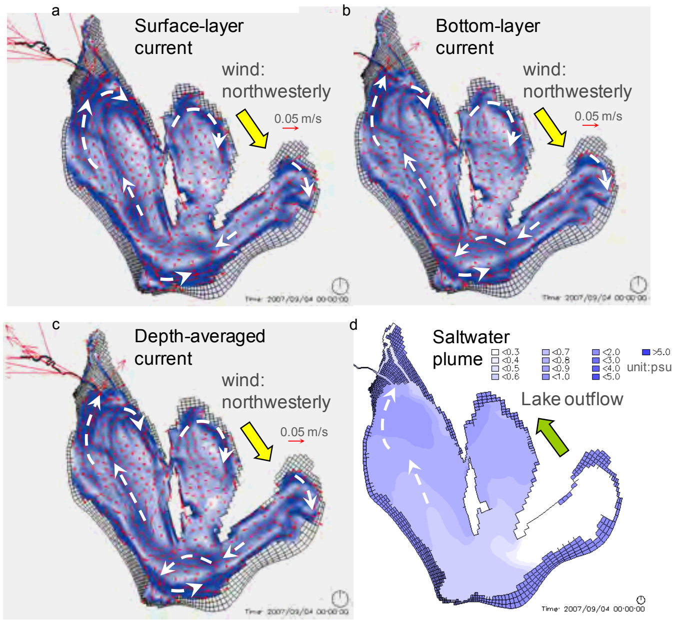

Figure 7. Wet season simulated Laguna Lake circulation ((a) surface layer current (b) bottom layer current (c) depth averaged current (d) saltwater plume). Indicated in arrows are the current (red), bay-wide circulation patterns (white), general lake flow direction (green), and wind direction (yellow)

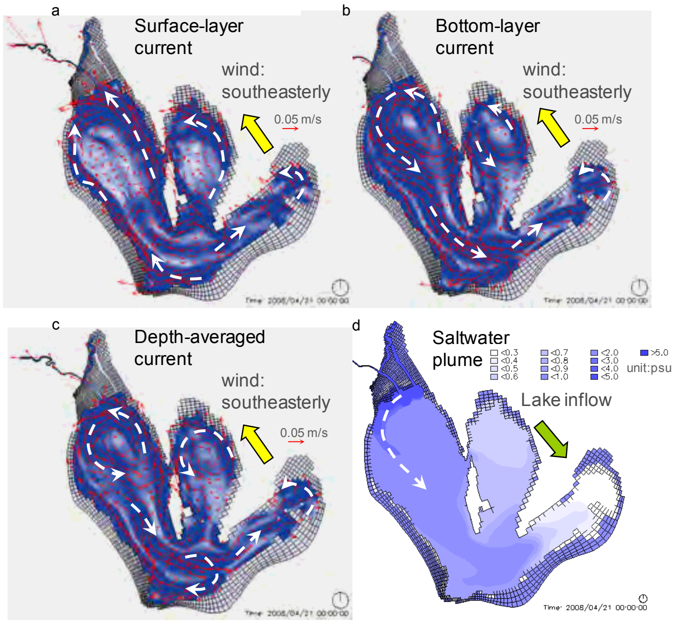

Figure 8. Dry season simulated Laguna Lake circulation ((a) surface layer current (b) bottom layer current (c) depth averaged current (d) saltwater plume). Indicated in arrows are the current (red), bay-wide circulation patterns (white), general lake flow direction (green), and wind direction (yellow)

The vertical profiles of chlorophyll-*a* and turbidity also showed nearly the same range of values (approximately 24 µg/L and 55 ftu, respectively) for the East Bay in both seasons when all other embayments declined in the wet season, indicative of the stable vertical mixing mechanism governing diatom dominance in this area. Diatoms have greater chances of dispersion and redistribution in the water column where nutrient concentration and light penetration is more conducive for growth.

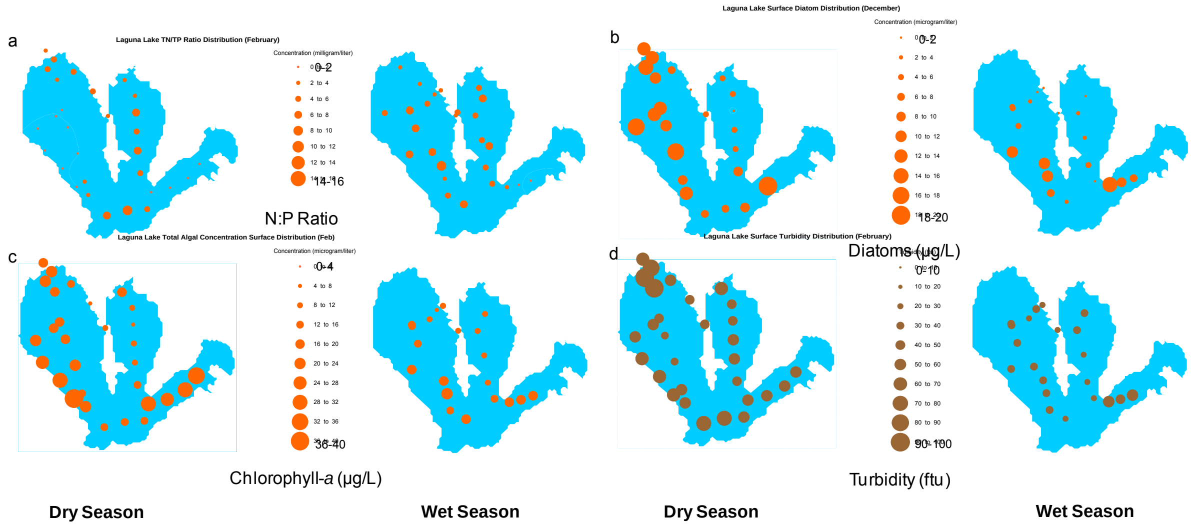

Figure 9. Spatial distribution of observed dry and wet season Laguna Lake water quality parameters ((a) N:P ratio (b) diatoms (c) chlorophyll-a (d) turbidity))

The similarities in turbidity and algal biomass distributions suggest a strong correlation between these two parameters. Algal biomass may be the primary factor contributing to water turbidity. Conversely, vertical mixing primarily brought by variations in wind stress and general lake circulation, which agitates bottom sediments and particulates, may have generated the turbid environment. Nutrient and bottom-concentrated phytoplankton were redistributed in the water column in the process where conditions became more favorable for growth and production. Either way, algal biomass and turbidity relationships are almost always related to production and/or mixing. As discussed, diatoms are the phytoplankton group most conducive to such a physical environment.

Mixed Layer Dynamics, Hypolimnetic Upwelling and Eutrophication

Water circulation is important in the distribution of bio-chemical variables and the transport of aquatic biota. Therefore, it is important to assess the characteristics of vertical current flow and the nature of the water movement. Analyses of the numerical simulation indicate the Laguna Lake circulation to be principally influenced by the watershed river discharge, Manila Bay tidal forcing, and wind stress. Numerical simulation demonstrated different circulation patterns and vertical current regimes for the wet and dry season hydrodynamic conditions resulting from changes in the lake water balance and atmospheric conditions. Seasonality in lake hydrodynamics was established for the horizontal lake circulation, vertical current regime, and stratification. Nonetheless, Laguna Lake sustained a high vertical mixing potential year-round primarily because of its shallow water depth as manifested by its turbid environment. The re-suspension of bottom matter due to mixing increased more markedly in the dry season with the lesser rainfall-associated drop in lake volume. With a strong diurnal wind signal, wind significantly brings horizontal directed current and vertical circulation by transfer of momentum and kinetic energy through surface stress in the lake. The effect is expected to be more considerable for shallower environments with the associated friction stress of a bottom compensating current. This was demonstrated by the horizontal current distribution along the vertical from numerical simulations, which showed a strong bottom compensating flow in the dry season. The difference in mixing depth, current velocity and flow structure between diurnal and seasonal hydrodynamic conditions depended on variations in the wind magnitude and the stability of the density gradient.

Mixed layer dynamics have important implications on planktonic movement, nutrient recycling, and accordingly, primary production [4]. This dynamic condition of the mixed layer (i.e., thickening and thinning) promotes the accelerated recycling of nutrients. Nutrients lost from the epilimnion are recaptured back every time there is a thickening of the mixed layer. Hence, nutrients are more likely to be returned to the eutrophic zone. Phytoplankton populations will have a continuous supply of available nutrients as a result. Under nutrient-limited conditions, maintenance of primary production will strongly depend on this recycling mechanism. This is in addition to the already high nutrient recycling efficiency of the lake through microbial nutrient regeneration brought by the sustained high temperatures. The same dynamics are responsible for the re-suspension of bottom sediments and organic matter by wind-transmitted turbulence. This may explain the dominance of the diatom phytoplankton group in the lake. As mentioned, this group is the most capable at synthesizing and settling at the lake bottom and the most adaptive to highly turbulent conditions and light gradients. Therefore, under conditions of continuous thickening and thinning of the mixed layer, diatoms have greater chances of dispersion and redistribution in the water column where nutrient concentration and light penetration is more conducive for growth. Based on the foregoing discussion, the potential of Laguna Lake for production with a given nutrient base is very high and correspondingly, will be more responsive to the water quality degrading effects of eutrophication.

Conclusions

Due to a higher degree of adverse responses to eutrophication, research on tropical lakes for the purposes of understanding ecological integrity and economic value need to be approached differently than the studies on temperate lakes. In this matter, the continuous field monitoring and numerical modeling analyses provide essential and adequate information for understanding tropical lake ecosystems. The interaction of the physical, chemical and biological variables under changing atmospheric conditions are pronounced and diurnally dynamic for tropical lakes. However, morphometry, hydrology and climate also provide an opportunity for seasonal dynamics. Therefore, the research approach taken in this study was based on these factors. Continuous field observations coupled with numerical simulations were employed for the assessment of the hydrodynamic features and corresponding implications to the water quality of a shallow tropical lake environment (Laguna Lake, Philippines). The results demonstrated different circulation patterns and vertical current regimes in time and space that accentuated a thermally stratified lake environment in spite of a shallow water depth. An analysis of the lake hydrodynamics also revealed the important implications of the mixed layer to planktonic movement, nutrient recycling, and accordingly, primary production. This study generated baseline information to form the scientific foundation of probable protective regulations and policies for Laguna Lake. Given the natural eutrophic inclination of tropical lakes, the integration of scientific methods at various time points is important to providing appropriate scientific information for the effective management of natural resources and environmental quality in the tropics.

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